Development and Validation of Analytical Tools to Characterize the Thermal Behavior of Composite Materials

Project Number: 97-18

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Purpose

The purpose of this CDDF is to develop and validate empirical relations to predict the thermal conductivity and specific heat of composite materials based upon component volume fractions and fiber orientation and geometry.

Background

Given their light weight and high strength, composites have found wide application in the aerospace industry. Early in the design cycle, the thermal engineer is often confronted with providing assessments involving the use of composite materials with little information beyond the geometry and composition of the material. Nonhomogeneous composites (i.e., filament wound rocket engine nozzles) with varying fiber composition or lay-up throughout the material complicate the issue further. Simplifying assumptions are often made where the anisotropic composite material is treated as an orthotropic material (known properties in the direction of principal axes). In order to address issues involving the prediction of the thermal properties of composite materials and the subsequent modeling of these materials, it is anticipated that this effort would result in generic techniques to allow the thermal engineer to, 1) estimate composite material properties based upon known quantities such as the component volume fractions, geometric lay-up, and component thermophysical properties, and 2) thermally model the resulting composite, accounting for directionally dependent thermal properties, using existing analysis codes. The techniques for predicting composite thermophysical properties will be validated against experimental measurements.

Approach

The initial effort will be centered around a literature search to research methods of analytically predicting the effective thermophysical properties of composite materials. Prediction of these properties will be based upon the composition and lay-up of the material as well as the volume fraction and thermophysical properties of each component. Additional research may uncover methods of accounting for the temperature and thermal history of the composite in the prediction of effective thermal conductance. Experimental methods of determining directional thermal properties of anisotropic materials will also be evaluated during the literature search. A select group of composite materials of varying composition, lay-up, and component volume fraction will be fabricated into coupons for laboratory testing to experimentally determine the thermophysical properties. Testing at room temperature and below will be performed in existing on-site facilities and/or facilities developed as part of this activity. The effort will conclude with the correlation of the theoretical predictions to the experimental results.

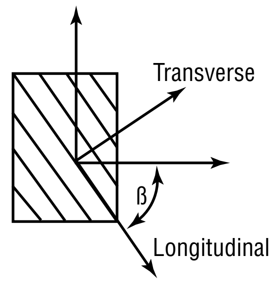
Accomplishments

A literature search to research analytical methods for the thermal modeling of composite materials and experimental methods for verification is approximately 20 percent complete. The search includes analytical formulations by Hasselman and Johnson of Virginia Tech, composite material prediction methodologies developed by TRW, and Hubble and AXAF–I testing composite materials by TRW and Dynatech.

The discretized governing equation for anisotropic heat conduction in a 2D solid is given by:

$$\rho c_p \frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} = k_{xx} \frac{T_{i+1,j}^{n} - 2T_{i,j}^{n} + T_{i-1,j}^{n}}{\Delta x^2} + k_{yy} \frac{T_{i,j+1}^{n} - 2T_{i,j}^{n} + T_{i,j-1}^{n}}{\Delta y^2} + k_{xy} \frac{T_{i+1,j+1}^{n} + T_{i-1,j-1}^{n} - T_{i,j-1}^{n} - T_{i,j-1}^{n}}{\Delta x \Delta y} + q''$$

If the longitudinal and transverse properties are known about an axis of symmetry, offset β ,from the primary axes, the thermal conductivity coefficients can be determined from a coordinate transformation1:



$$k_{xx} = k_L \sin^2 \beta + k_T \cos^2 \beta$$
$$k_{yy} = k_L \cos^2 \beta + k_T \sin^2 \beta$$
$$k_{xy} = \left(k_L - k_T\right) \sin 2\beta$$

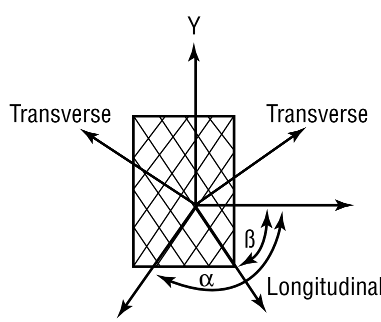
1Rohsenow and Hartnett, “Handbook of Heat Transfer”, 1973

FIGURE 21.—Heat conduction in an anisotropic solid.

Multiple fiber systems can be modelled by summing the thermal conductivity coefficients:

$$\varphi_p \frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} = \left(k_{xx}{}^1 + k_{xx}{}^2\right) \frac{T_{i+1,j}^{n} - 2T_{i,j}^{n} + T_{i-1,j}^{n}}{\Delta x^2} + \left(k_{yy}{}^1 + k_{yy}{}^2\right) \frac{T_{i,j+1}^{n} - 2T_{i,j}^{n} + T_{i,j-1}^{n}}{\Delta y^2} + \left(k_{xy}{}^1 + k_{xy}{}^2\right) \frac{T_{i+1,j+1}^{n} + T_{i-1,j-1}^{n} - T_{i,j-1}^{n} - T_{i,j-1}^{n}}{\Delta x \Delta y} + q''$$

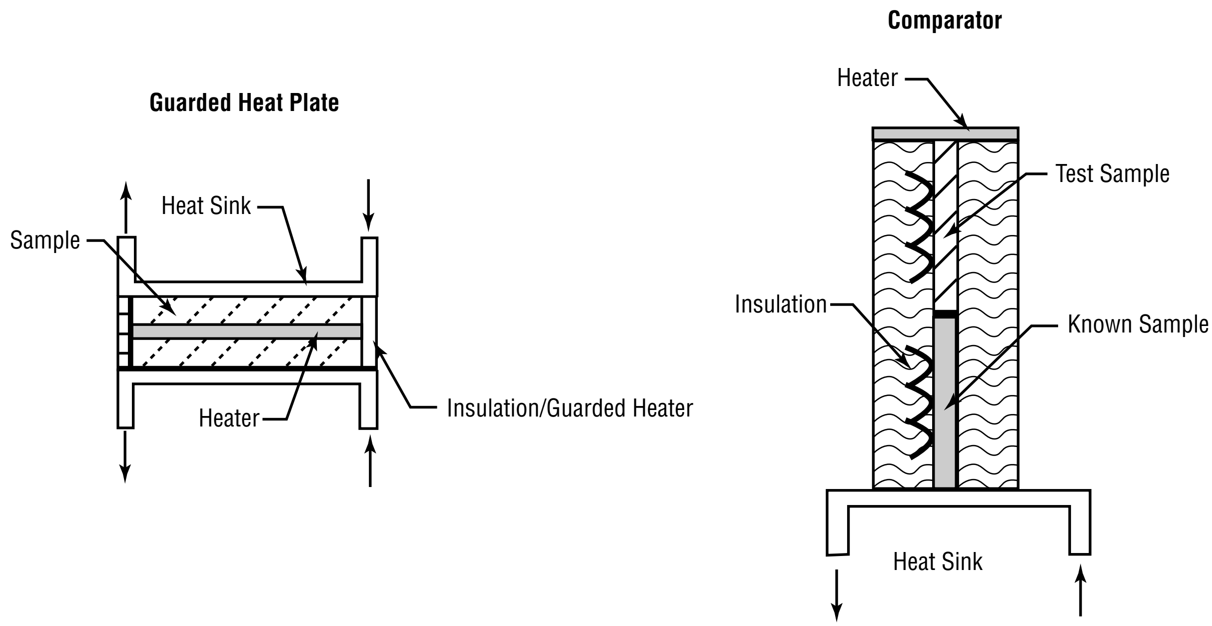
$$k_{xx}{}^1 = k_L{}^1 \sin^2 \beta + k_T{}^1 \cos^2 \beta$$
$$k_{yy}{}^1 = k_L{}^1 \cos^2 \beta + k_T{}^1 \sin^2 \beta$$
$$k_{xy}{}^1 = \left(k_L{}^1 - k_T{}^1\right) \sin 2\beta$$
$$k_{xx}{}^2 = k_L{}^2 \sin^2 \alpha + k_T{}^2 \cos^2 \alpha$$
$$k_{yy}{}^2 = k_L{}^2 \cos^2 \alpha + k_T{}^2 \sin^2 \alpha$$
$$k_{xy}{}^2 = \left(k_L{}^2 - k_T{}^2\right) \sin 2\alpha$$



The equation simplifies to the orthotropic case if identical fibers are used in an orientation that is symmetric (α=β+180o) about the X and Y axes.

FIGURE 22.—Anisotropic heat conduction in a multiple fiber system.

Both TRW[1] and Dynatech[2] have demonstrated guarded heat plate and comparator methods to measure the longitudinal and transverse thermal conductivities of long fiber carbon/graphite composites



[1] “Thermophysical Property Measurements on P75/954-3 Graphite Epoxy Laminate for Hercules Aerospace Company,” TRW Space and Electronics Group, 1993.
[2] “Thermal Conductivity of Graphite Epoxy Samples,” Dynatech Inc., July 1982.

FIGURE 23.—Experimental measurement of thermal conductivity.

Planned Future Work

The CDDF will continue with the completion of the literature search. To date, higher priority projects have prevented completion of the study phase of the project. After the study phase is complete, we can begin the subsequent work of identifying and purchasing which composites to test and which to fabricate. The outlook is more optimistic since it is anticipated that the principal investigator will be able to spend 40 percent of his time in FY98 due to the “stand-down” of another high-priority project.

Funding Summary ($k)

FY97	FY98
60	40

CDDF 97-18 has an unprocessed FY97 balance of 60k. 25k of the FY97 funding has been deferred until FY98. A total of 65k is guaranteed for FY98 (25k of the FY97 funding plus the original FY98 funding).

Manpower Summary

	FY97	FY98
Predicted:	0.5 man-year (2 engineers)	1.0 man-year (2 engineers)
Actual:	0.05 man-year (1 engineer)	

Status of Investigation

We will continue through FY98 with our remaining FY97 funds. Our estimated completion date is September 30, 1998.